Mirror Technology Development for the International X-ray Observatory Mission (IXO)

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ABSTRACT

The International X-ray Observatory (IXO) is designed to conduct spectroscopic, imaging, and timing studies of astrophysical phenomena that take place as near as in the solar system and as far as in the early universe. It is a collaborative effort of ESA, JAXA, and NASA. It requires a large X-ray mirror assembly with an unprecedented X-ray collection area and a suite of focal plane detectors that measure every property of each photon. This paper reports on our effort to develop the necessary technology to enable the construction of the mirror assembly required by IXO.

Keywords: X-ray Optics, Segmented X-ray Optics, Glass Slumping, International X-Ray Observatory, IXO

1. INTRODUCTION

The International X-ray Observatory [1] is designed to conduct spectroscopic, imaging, and timing studies of many different objects. As such it requires an unprecedented photon collection area (~3 m^2) and angular resolution (5" HPD) that is better than all but the Chandra X-ray Observatory (0.5" HPD). No existing technology simultaneously meets the needs of IXO, which can be summarized, at the highest levels, to four requirements: (1) angular resolution, (2) effective area, (3) mass, and (4) production cost and schedule. In this paper we report on a technology development program that has been underway for a few years which, when completed, will meet all these four requirements.

2. CONCEPTUAL DESIGN OF THE FLIGHT MIRROR ASSEMBLY

The flight mirror assembly (FMA) required by IXO has an outer diameter of approximately 3 meters. The current conceptual design [2, 9] divides the assembly into three concentric rings: inner, middle, and outer. The inner ring is further divided into 12 identical modules, each of which covers 30 degrees in azimuth. Likewise the middle ring and the outer ring are each further divided into 24 identical modules, each of which covers 15 degrees in azimuth. As such the entire FMA is divided into 60 modules of three different types. Each of these modules is quite similar in dimension and mass. In particular the dimension (less than 50 cm to a side) and mass (on the order of 30 kg) of these modules are such that they can be built, handled, and tested

Space Telescopes and Instrumentation 2010: Ultraviolet to Gamma Ray,
edited by Monique Arnaud, Stephen S. Murray, Tadayuki Takahashi, Proc. of SPIE Vol. 7732,
77321G · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.857536

without having to use specially designed and built equipment and facilities. Because of the relatively large number of identical modules, the management of spare parts becomes a simple matter of making an appropriate number of modules of each type, greatly reducing the cost and logistical complexity of making the large FMA.

The task of aligning and integrating the 60 modules into the FMA is substantially similar to many other tasks that have been accomplished for past and existing missions. Although requiring careful planning and engineering, it does not require new technologies. All it requires is an appropriately designed and fabricated superstructure to which all the 60 modules will be aligned and attached and an appropriate facility to accommodate the typical structural and thermal requirements of such an effort.

The challenge unique to building the IXO mirror assembly is the construction and test of the 60 mirror modules. Each of these modules contains approximately 150 pairs of mirror segments. These mirror segments are only 0.4mm thick and have an axial length of 200mm and an azimuthal arc-length ranging from 190mm to 390mm. In the next Section all aspects of constructing a mirror module are defined and described. The objective of this technology development program is to develop and perfect techniques to address every one of these aspects.

3. DESCRIPTIONS AND DEVELOPMENT STATUS OF TECHNOLOGY COMPONENTS

Table 1 is a brief summary of our technology development strategy and plan. The foundation of this technology is a precision glass slumping technique that replicates the precise optical figure of mandrels that are fabricated using the traditional grinding and polishing techniques, which are typically expensive and time consuming. The replication technique brings down the total precision ground and polished surface area from close to 1,000 m^2 to close to 30 m^2, significantly reducing the cost and schedule required to manufacture the physical mirror area by IXO.

3.1 Fabrication of Forming Mandrels

Forming mandrels are the starting points of the FMA manufacture process. In general the making of these mandrels does not present a technical challenge per se as the figure quality and the total square meters of figured area are comparable to those of many other missions in the past. The unique aspect of the IXO mandrels is in that, because the entire FMA manufacture process starts with mandrels, all these mandrels have to be made available as early as possible. We have two objectives for this part of our technology development program. The first one is the development of an accurate and efficient metrology process that definitively and quantitatively measures the mandrel optical surface. The second one is the making of a small number of mandrels to support the rest of this technology development program.

Forming Mandrel Metrology

Accurate and fast measurement of a forming mandrel's optical figure is essential to the efficient fabrication of forming mandrels. The unique aspect of X-ray optics is the near cylindrical shape of the optical surface. We take advantage of this fact by using a cylindrical wavefront generated using a plane wavefront of a Fizeau interferometer and a cylindrical lens, also known as a null lens. The cylindrical lens converts the plane wavefront into a converging cylindrical wavefront that can be retro-reflected from the nearly cylindrical mandrel surface. Interferometric comparisons of the return wavefront with the original plane wavefront quantify the errors of the mandrel surface. This method adequately measures all the parameters of the mandrel except the average radius and average cone angle. The average radius and average cone angle, which determine the focal length, are measured using a coordinate measuring machine (CMM) that typically has an accuracy of several microns, depending on the specific condition of use and other factors. In general, this is accurate enough for measuring both the average radius and cone angle.

Table 1. A summary of the IXO mirror technology development strategy and plan. The successful development of the techniques identified in this table will enable us to build and test a flight-like module.

Major Categories		Minor Categories	Technology Development (Adaptation, Invention, Development, Maturation, Demonstration, and Documentation of Basic Procedures)	Engineering and Planning	Mass Production
			Pre-Phase A	**Phase A/B**	**Phase B/C**
Construction of Mirror Modules	**Fabrication of Forming Mandrels**	**Metrology**	**Definitive measurement of mandrel surface:** Completeness; Accuracy; Speed	(1) Detailed specifications of all equipment and prcourement strategy; (2) Detailed designs and drawings; (3) Detailed analysis and validation with prototypes; (4) Detailed mass production plans; (5) Detailed management and budget plans; (6) Rigorous and independent technical and management reviews	Execution of plans and implmentation of designs
		Material	**Identification and qualification of the best suited material for making mandrels;** Stability; Availability; Ease of fabrication; Cost		
		Fabrication	**Manufacture of forming mandrels;** Figure quality; Speed; Cost		
	Fabrication of Mirror Segments	**Slumping**	**Replication of the forming mandrel figure onto substrates;** Repeatability; Accuracy; Speed; Cost		
		Cutting	**Trimming of bad edges and to right dimensions;** Edge quality; Dimensional Accuracy; Speed; Cost		
		Coating	**Maximization of X-ray reflectivity;** Reduction or elimination of coating stress; Microroughness; Adhesion; Speed; Cost		
		Metrology	**Complete measurement of mirror surface;** Completeness; Repeatability; Accuracy; Speed; Cost		
	Assembly of Mirror Segments	**Mounting**	**Conversion of mirror segment to a "Rigid Body;"** Number of bonds; Figure preservation; Speed; Cost		
		Aligning	**Adjustment of the mirror segment to correct or design location and orientation;** Closed-loop operation; Repeatability; Stability; Speed; Cost		
		Bonding	**Preservation of figure and preservation of alignment and achieving good bond strength;** Figure; Alignment; Bond Strength; Speed; Cost		
	Module Design, Analysis, Construction, and Test	**Housing Material**	**Determination and Selection of the best possible material for constructing the module housing;** Availability; Optical performance, Thermal performance; Structural performance; Ease of machining; Cost		
		Design	**Accommodation of all logistic and performance factors;** Elegance; Ingenuity; Maximization of effective area; Miminization of distortion; etc..		
		Analysis	**Comprehensive analysis to arrive at specifications for construction and calibration environment;** Temperature tolerance; Gravity effect; etc..		
		Construction	**Bringing together everything learned and developed to perform end-to-end demonstrations;** Single pair, multiple pairs; "flight-like;" etc...		
		Tests	**X-ray performance:** angular resolution and effective area; **Envirionmental tests:** Shock; vibration; accoustic; thermal-vacuum; long-term stability; etc.		

The null lens uses a two-element design to minimize spherical aberration. Both elements have been fabricated and are being aligned and integrated into a housing. The assembly is to be completed and tested and fully utilized in the coming year. One significant feature of this null lens is that it will also be used to measure mirror segments. Mirror segments, whose optical surfaces are concave, will be compared with the diverging part of the null lens wavefront beyond its focus.

Forming Mandrel Material

We are investigating several materials for their suitability for making forming mandrels. The ideal mandrel material must have the following properties. It must be stable over the large temperature range of the slumping process: room temperature to about 600 degrees centigrade. It also must be homogeneous and isotropic enough to preserve its figure in the same temperature range. It must be able to sustain hundreds of temperature cycles. In addition, a very desirable property is that it be machinable. This property would greatly reduce the cost and schedule of making forming mandrels.

The materials we are looking into include fused quartz and stainless steel. We have found that commercial grade fused quartz meets all requirements. The disadvantage of fused quartz is that it is not machinable. It has to be ground into near-net shapes before fine polishing and figuring can begin. This is a primary reason why we are also looking into using stainless steel [3] which is fully machinable. Preliminary results indicate that stainless steel cannot maintain its figure over repeated thermal cycles between room temperature and 600 degrees centigrade. We will conduct more tests and measurements in the coming year before reaching a final decision as to the usability of stainless steel as a forming mandrel material.

Forming Mandrel Fabrication

The fabrication of each forming mandrel follows the standard optical fabrication process: first make a near-net shape blank and then go through the measure-and-polish iterations until the figure meets requirements. We are looking into a number of deterministic material removal polishing techniques, including those developed by QED Technilogies, ZEEKO, and RAPT Industries, Inc. In general, all these technologies probably will work well once hit-maps are generated quickly and reliably from the measurement process using the techniques outlined in the previous section. We are canvassing industry to identify interested firms and available facilities for the purpose of making the large number of forming mandrels for IXO.

Meanwhile we are also making a small number of mandrels [4] to support the development of the glass slumping process. To date we have completed two pairs of mandrels, dubbed 489P/S and 494P/S, respectively, that meet IXO figure quality requirements. A third pair is being fabricated and expected to reach requirements by 2010 fall. These three pairs of forming mandrels will enable us to build module demonstrating the technical readiness of this technology.

3.2 Mirror Segment Fabrication

The objective of the mirror segment fabrication is to replicate the precision surface figure of the forming mandrel onto a thin glass mirror segment as accurately as possible. In essence this is a lightweighting process. We have adopted a glass slumping process [5]. It starts with a commercially available thin glass sheet, Schott D263, 0.4mm thick. It culminates in a mirror segment coated with a layer of iridium that has the highest X-ray reflectivity in the energy band of interest of IXO.

Slumping

The slumping process takes advantage of the fact that glass is a viscose liquid whose viscosity is a function of temperature. When it is heated near its glass transition temperature, it easily deforms under its own weight and conforms to the mandrel that supports it. As of June 2010, we have been able to make mirror segment pairs that, when properly aligned and assembled, are capable of producing 6.5" HPD images. This is to be compared with the requirement of 3.3" HPD, showing that we are within a factor two of meeting requirements. With further refinement of a mandrel release layer and optimization of slumping temperature cycles, we expect to be able to make mirror segments at the 3.3" level by the end of 2011.

Cutting

The slumping is a gravity-assisted thermal process. As such there are always edges of the formed replicas that have to be removed. We have invented a hot-wire cutting technique that removes those edges and create a finished mirror substrate that has the following properties: (1) the resulting edges are smooth and free of micro-fractures that could propagate and lead to breakage; (2) the dimensions meet requirements for aligning and integrating the mirror segment into housing.

One concern that is being addressed is whether the hot-wire cutting process has inadvertently created stress in the areas where the wire touched the glass, resulting in local or even larger than local figure distortions. We are investigating this problem by varying the temperature of the wire during cutting to see whether the amount of distortion is correlated with wire temperature.

Coating

A bare glass surface does not efficiently reflect X-rays. Its reflectivity can be significantly enhanced by a film of iridium. The sputtered iridium has to have a thickness of 15nm or more to prevent any "leakage" at higher X-ray energies than several keV. In general the sputter process is a well-understood one. We have met both microroughness and density requirements. We are in the process of reducing or even eliminating coating stress caused by the fact that iridium has an extremely high melting point. The resulting coating stress has caused significant distortions to the mirror figure.

We are eliminating this coating stress by undercoating the iridium layer with a thin chromium layer, approximately 10nm. The chromium layer has opposite stress to the iridium layer. With an appropriate thickness and coating conditions, the chromium layer can nearly perfectly balance out the iridium layer, resulting in nearly stress-free coating. The physics of such balancing is well understood and has been amply demonstrated by others. We are in the process of implementing a recipe to perform the Cr-Ir by-layer coating on a routine basis.

3.3 Assembly of Mirror Segments

Once a mirror segment is fabricated and qualified, the next step is to align and bond it into the mirror housing. This alignment and bonding process must adequately preserve the figure of the mirror segment and enable it to withstand launch loads. We have divided this process into three steps: temporary bonding, alignment, and permanent bonding.

Temporary Bonding

The mirror segment is very flexible, being only 0.4mm thick and having an aspect ratio of the order of one thousand. Any manipulation of its position and alignment could result in unacceptable distortion. Therefore the first step of the assembly process is to effectively convert this flexible mirror segment into a de-facto rigid body. The mirror segment is suspended by 2 or more flexible strings from the "ceiling" such that its optical axis is as vertical as possible, resulting in the least amount of distortion caused by gravity. Detailed finite element analysis has shown that the total distortion depends on the number of strings and on the angular span of the mirror segment. For the specific mirror segments spanning the entire IXO range, four strings are sufficient to keep the gravity distortion at negligible levels.

Once the mirror segment is suspended, it is carefully bonded to a stiff structure, a strongback, made of the same material (Schott D263 glass) as the mirror segment. The mirror segment is attached to the strongback on the non-reflection surface or at the top and bottom edges [6]. Over the last year we have experimented with a number of methods to do the attachment. Currently we are investigating two methods that have demonstrated promise to meet requirements: edge-bonding and smart-pin bonding.

Edge-bonding method bonds the mirror segment to the strongback at a number of points on the top and bottom edge. The bonding process is such that it applies little, if any, force in radial directions. All the forces related to the bonding process act in the axial direction where the mirror segment can tolerate the most forces. Excellent results have been achieved. Whether the entire process meets IXO requirements is being investigated with a final determination expected by the end of this year.

The smart-pin bonding method uses a number of nano-actuators to attach the mirror segment to the strongback. These actuators are engineered with force sensors such that each actuator's force on the mirror segment in its local radial direction is monitored and minimized in the entire bonding process. Initial promising results have been achieved. More experimentation is underway.

Alignment

Once a mirror segment is bonded to the strongback, it can be manipulated, for all intents and purposes, as a rigid body. All conventional alignment equipment and techniques can be adopted and used to accomplished the following two requirements: (1) to position the mirror segment in the best or design location, and (2) to orient it into the best orientation to achieve the best focus. In practice we have adopted two hexapods, each of which is capable of translating with micron precisions and orienting with sub-arcsecond precisions. The two hexapods are adjusted according to the feedback from a set of Hartmann maps [6] which are provided by a beam of parallel light establishing the optical axis of the system being constructed [7,8].

A current difficulty comes from some structural and thermal instability in the alignment tower that houses the Hartmann light beam, the hexapods, and the mirror segments being aligned. We are in the process of creating a temperature-stablizing structure around the entire alignment equipment. When finished, the temperature should be stable within 0.1 degrees centigrade.

Permanent Bonding

Once the mirror segment is located and oriented to its optimal position and orientation, it is permanently bonded to the mirror housing structure through specially designed and fabricated tabs. When the permanent bonds have cured properly, the mirror is debonded from the temporary strongback. The permanent bonding process [7] must bond the mirror segment to the housing at a number of locations without moving or distorting the mirror segment. We have implemented a bonding process using a UV-cure epoxy, a nano-actuator, and a laser displacement sensor. Before the bonding process starts, the laser displacement sensor measures the position of the mirror segment at or near the bonding location. During and bonding process and the epoxy cure process, the laser displacement sensors constantly feeds its readings to the nano-actuator which pulls or pushes the mirror segment so that it stays where it was before the start of the bonding process. This way the mirror segment is guaranteed to keep its alignment and figure.

We have demonstrated on stand-alone stations that this process can be accomplished successfully with a precision of better than 100 nm, which is the precision required to fulfill IXO requirements.

4. DESIGN, ANALYSIS, CONSTRUCTION, AND TEST OF THE MIRROR MODULE

The module housing provides the mechanical structure to enable the mirror segments to withstand vibration and acoustic loads of the launch. It also provides the necessary thermal environment for the mirror segments to perform to their full optical potential [9].

4.1 Housing Material

The ideal housing material must have the same coefficient of thermal expansion as the Schott glass to minimize the effect of any bulk temperature change between construction and operation. We are investigating two potential materials: carbon fiber reinforced composite and a specially formulated iron-nickel alloy. Small coupons are being made and measured for their CTE to arrive at proper recipes. We expect to reach a final conclusion as to which is the better housing material by the end of 2010. Our evaluation criteria will include structural performance, thermal performance, as well as ease of fabrication and overall cost.

4.2 Design and Analysis

Once an optimal material is determined for making the module housing, a housing structure will be designed and then analyzed for all of its properties: structural integrity under various load conditions, its thermal performance under various conditions, and its influence on the optical performance of the mirror segments. The finished design will meet mass requirements as well.

4.3 Construction and Test

The ultimate objective of this technology development program is the successful construction and test of a flight-like mirror module. The construction process will exercise every procedure and technique that has been developed in the previous sections. As of June 2010, we have separately exercised and tested many of them under various situations. In 2011 and 2012 we will systematically integrate all of them in a way that would demonstrate that they are compatible with the entire construction process, creating a module with satisfactory performance in terms of angular resolution and effective area and passing all environment tests. In particular, all the procedures are amenable to being implemented as part of a mass production process that is necessary to manufacture the 60 flight modules.

The module to be built as part of this technology development has a number of features. It will have at least three pairs of optically qualified mirror segments with which we will test the optical and X-ray performance. The rest of the mirror segments will be mass dummies, i.e., they will not have the optical figure quality of real mirror segments. This is because we don't expect to be able to procure all the forming mandrels necessary to populate an entire module. While the making of the forming mandrels does not present any technical challenge, it does present a budgetary challenge for a pre-Phase-A technology development program. Moreover we believe populating the entire module with optical qualified mirror segments may be desirable, but not essential nor necessary to demonstrate the validity of the technology. This module will meet mass requirements dictated by project systems engineering considerations. Its resonance frequencies and thermal gradients under pre-determined vibrational and thermal conditions must also meet requirements. It will undergo rigorous tests as if it were a spaceflight module. In particular, it will undergo full illumination X-ray tests to measure its angular resolution and effective areas at various energies ranging from below 1 keV to 10 keV.

5. SUMMARY

We have presented a brief summary of our mirror technology development program for the International X-ray Observatory. The progress so far and plan for the next couple of years are consistent with expectations that we be able to fully meet IXO requirements by the end of 2012, enabling the project to start shortly thereafter to accommodate a launch in the early 2020s.

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